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Winding Pack Height Management during Fabrication of the ITER CS Module

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Abstract

The Central Solenoid (CS) stack consists of six modules, 2.1 m tall each [1]. In order to verify good impregnation, we performed a vacuum pressure impregnation (VPI) test of a full cross section of the CS module (CSM), 40 conductors tall and 14 conductors wide [2]. It was discovered that after preparation of the full cross section stack until completion of the VPI, the stack shrunk in height by 20-25 mm. Our study of the literature and discussions with the leading experts in VPI did not reveal obvious reasons for this change of height, so we launched a study to address this issue. We assembled two 12x1 (tall by wide) arrays and several 7x1 arrays in order to study characteristics of the dry winding pack under compressive force and effects of different fabrication steps. Then we impregnated these arrays in different conditions under compressive force and studied change of height as a result of compression, impregnation, gelling and curing of the stack of insulated conductors. We showed that by controlling the application of the compressive force, before closing the mold and during impregnation, one can reduce the height uncertainty. Most of the height reduction takes place while the glass is dry under the dead weight and the applied compressive force. Reduction of height during injection of the resin and during gelling, curing and cooling of the coil is noticeable, reproducible and relatively small. The paper presents results of our studies and recommendations for assembly and VPI of tall windings.
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Keywords: Vacuum Pressure Impregnation, Superconducting Magnets, Epoxy Resin Permeation

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1. Introduction

During the 40x14 vacuum pressure impregnation project that simulated impregnation and cure of the full cross section of the central solenoid module [2], it was discovered that the height of the conductor stack decreased by about 20 mm near the mold walls and 25 mm in the middle of the stack (~ 1-1.25% of the nominal 2100 mm stack height). It is not clear if it happened on the dry glass under the dead weight pressure (which was equivalent to about 1.2 bars at the bottom of the module at the full height), during resin injections into the mold, during the gelling at 90 ^{o}C or during curing the resin at 128 ^{o}C. Different speculations were considered: creep under the dead load, effect of lubrication of the glass yarns by the resin that promoted their motion and sagging, effect of non-uniform curing of the cross section, and shrinkage of the epoxy during gelling and curing. This sagging is very undesirable for many obvious reasons and needs to be significantly reduced or eliminated for production. In order to study what fabrication steps were responsible for sagging and how to suppress this effect, Magnet Development Laboratory (MDL) built two stacks of the 12x1 conductor in a mold for VPI and with the appropriate insulation from the carbon steel jackets with holes to simulate conductors. We also studied compression characteristics of the stack by applying and releasing a pressure on the array up to 2.4 bars. In both arrays, the pressure is applied through a spring-loaded mechanism in order to compensate for the creep. The pressure applied by the jackbolts with springs before VPI was maintained during the VPI process. The molds were designed to provide a small clearance between the stack and the walls in order to eliminate any friction effect.

We took records of the height before, during, and after VPI with LVDT or other displacement sensors during the whole process from the assembly and preload until end of curing cycle and cool down to room temperature (RT). The load cells read the applied load.

Simultaneously, General Atomics launched a study based on the 7x1 arrays to study that phenomenon and then followed up with studies on 3x1 arrays. They built and tested six 7x1 stacks and applied loading conditions that simulate a possible pre-compression scenario during fabrication of the CSM and then a compression of the CSM during pump down, injection of the resin, gelling and curing cycles and then cooldown to RT. The height of the stack was also studied under compression applied by the pneumatic cylinders.

2. Tests description

2.1. Description of Insulation

The turn insulation schematic is shown in Fig. 1. It has a glass-kapton system, but also a co-wound quench detection tape, which has two stainless steel strips (2.8 mm x 0.05 mm) woven into a 50-mm-wide glass tape with the overall thickness of 0.2 mm.

The MDL arrays had one layer of the ground insulation simulated at the bottom of the array. It consisted of three layers of perforated G-10 sheet and four layers of perforated kapton with perforations 200 mm from each other. The perforations were staggered such that the holes would be 100 mm from each other at every layer. Each barrier was separated by four layers of 7500 glass, which gave a total of 32 layers of glass. The total thickness of the ground insulation under the nominal pressure of 0.1 bars was 13 mm. (The GA arrays did not have the ground insulation simulation.)

The insulated conductors had a 7781 satin weave glass cloth in between them, representing the winding pack design. The MDL Array #1 had two layers of the glass cloth and the MDL Array #2 had nine layers in order to simulate the specified distance between the bare conductors (metal to metal distance) of 3.5 mm.

This distance, nominally 3.5 mm is difficult to keep very precisely during fabrication due to the varying dead load. Design of the CSM and the compression structure of the CS assembly can accommodate slight variations of this distance. Among the goals of the tests was to observe variation of the inter-turn distance as a result of the compression and VPI process and find effective ways to control it. It will be finalized after verification on the mockup prototyping of the CSM full scale.

2.2. MDL studies

MDL built two arrays as shown schematically in Fig. 2. The main difference in design of the arrays was that the first had two layers of 7781 glass in between the insulated conductors and the second had nine layers. The main difference in loading was that the Array #1 load history did not allow complete release of the pressure, simulating more the bottom layers of the module (as it is assembled). In the Array #2 we made a full characterization of the array that would allow us to predict behavior of the dry array at any of the vertical position of the array.

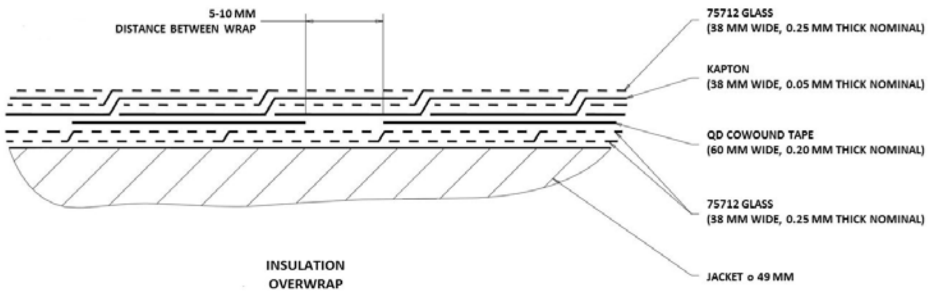

Fig. 1. Turn insulation schematic.

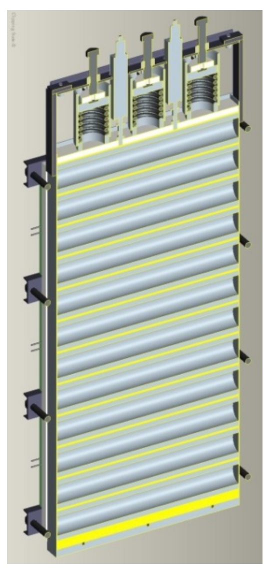

Fig. 2. 12x1 array cross section.

2.2.1. MDL Array #1

Displacement history of the MDL array #1 is shown in Fig. 3. The load scenario was as follows: a) dry array preload, then b) several unloads but not all the way to zero in order to simulate the lowest portion of the module as it sits on the VPI base, being compressed during assembly, which always experiences a dead weight of the layers above. Then the final compaction is done and after the assembly is complete, the array is VPIed under compression with lower pressure than the compression during dry stack assembly.

It can be seen in Fig. 3, the first 250 microns of the displacement shows artificially stiff behavior. This is not physical; it is a rocking of the load plate under initial settling of the array, which distorted the initial part of the load curve. In the Array #2 we avoided that paying attention to uniform loading of the jack bolts.

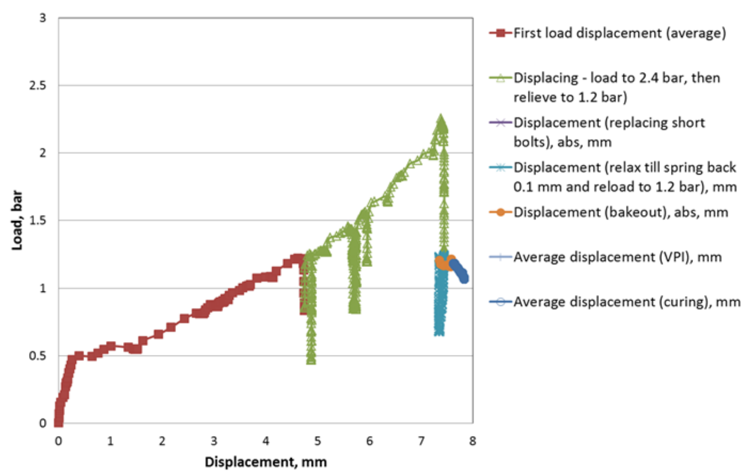

Fig. 3. History of the MDL array #1 displacement. Displacement reflects compaction or shrinking of the stack height.

The following observations can be made:

a) The load – displacement curve is far from saturation as usually is the case for glass cloth at some load. Usually, (and that was observed in a numerous tests) the insulation stiffness increases significantly with the load. In our case, there is a slight indication at around 1 bar, but far from saturation.

b) Once the glass is compressed and is not released completely from the pressure, the displacement of the stack is not changing much. One can see in Fig. 3, that release of the pressure to 0.5 or 0.7 bar does not change the stack height. That means that by compacting the stack to a high enough pressure we obtain a reproducible and stable height.

c) Pump down, impregnation, gelling and curing and cool down are responsible for 0.5 mm reduction of the height of the stack, comparing to the compaction of the dry stack, measured in 7-8 mm. That points out that the main compaction and stiffness is controlled during operations with the dry insulation (at the selected compaction). Impregnation and VPI have little effect on the stack height.

d) Cycling, or multiple repeatable applying of the compressive load of the same amplitude to a dry stack does not seem to be significant and beneficial in the Array #1. Few compressions of the stack to a certain level are as efficient as many compressions, not much is gained by multiple application of the pressure.

After completion of the VPI, the metal-to-metal spacing was measured. The thickness of the glass between the jackets was on average 2.16 mm and there was no correlation between the thickness and the position of the gap in the array. In other words, fabrication uncertainty and scatter, probably, masked expected correlation of the smaller gap at the bottom (where the load is the highest) and at the top (where the load is lowest). It also needs to be noticed that the overall pressure of 1.2 bars is higher than the dead weight pressure of 12 jackets (0.36 bars) and that made the gap thickness more or less uniform.

The main conclusions from the tests of Array #1 are: a) dry glass needs a reasonable compaction to avoid creep and thickness variation; b) compaction during VPI is very effective in suppressing the change of the stack dimensions; c) VPI, gelling and curing change the height of the stack by a small amount comparing to the dry glass compaction d) varying the pressure of compaction it is possible to control the height of the stack.

2.3. MDL Array #2

The second array assembled by MDL had more glass between the conductors. It changed the behavior of the array significantly. In addition, we had a slip plane between the array and the mold walls to eliminate any friction concerns. Fig. 4 shows behavior of the dry glass loading. The difference from the Array #1 has two distinctive features: 1) the total stiffness of the winding pack is much lower than that of Array #1, which is expected and 2) the unloading curve has very non-linear behavior, especially when the coil is loaded to high compression or unloaded near complete relieve. The nonlinearity of the glass has a step at 1.5 bars, where the slope of compression increases significantly faster than at lower pressure; it was a typical behavior for the compactable insulation.

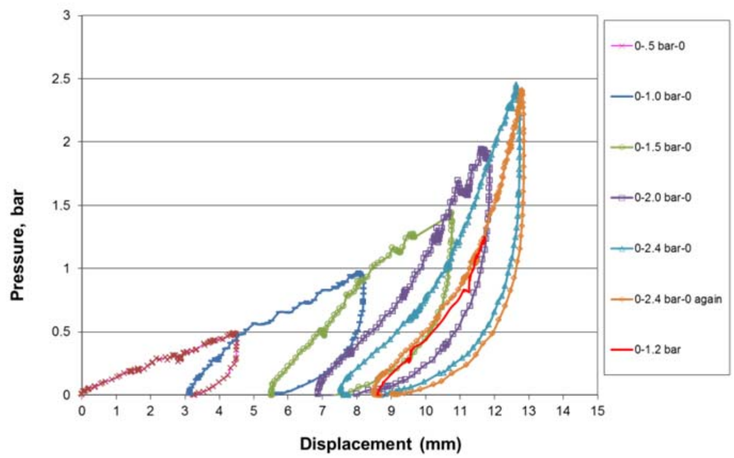

Fig. 4. History of the MDL Array #2 loading of the dry glass.

The following features could be noted from the Array #2 observations:

1. Thick insulation behaves qualitatively different from “thin” insulation of Array #1. The behavior is highly non-linear.
2. Spring back is significant and increase of the load does not eliminate spring back completely as it is observed in the past tests of turn-to-turn insulation and in the Array #1. Earlier observations at MDL and GA led to conclusion that once insulation is compressed from the original “fluffy” condition, the spring back is small, it remained compressed.
3. Two consecutive loads to 2.4 bars with the complete release of the pressure to zero resulted in a significant compaction of the winding pack by 1 mm. However the following loading to 1.2 bars did not change characteristics of the load line. That means that the winding pack insulation achieves the saturation and reproducible behavior after just one cycle. Multiple compressive cycling is not necessary.
4. By manipulating the applied pressure one can control the height of the winding pack of 40 layers (full module height) within 15-20 mm.

The resulting load loops of the 12x1 winding pack provide a good estimate of what will happen to the winding pack at the top, at the bottom or in the middle of the winding pack during fabrication, dry glass compression strategy and VPI and curing and cooling cycles.

Change of the 12x1 stack height was studied during VPI and curing cycle under compression of 1.2bar revealed the following behavior. Fig. 5 shows change of the height during bake-out under vacuum and VPI injection and 3 pressure cycles and cure cycle. As one can see the change is noticeable, but insignificant in comparison with the dry glass compression. Once the mold is closed and the pressure is applied, the total displacement is under 1 mm for the 12x1 stack with a ground insulation; that projects to about 3 mm overall shrinkage for the whole CSM. As with Array #1, the compressed glass behaves in a more or less predictable way.

The metal to metal spacing was measured in the MDL Array #2. Measurements showed on average 3.5-3.55 mm. Although the dead weight always makes the pressure at the bottom higher, the systematic gap measurements did not support this expectation with the selected load history. That indicates that the scatter during fabrication is larger than the systematic effect of the pressure, and that the gap was formed under a pressure that is high enough to effectively suppress difference in the gap height.

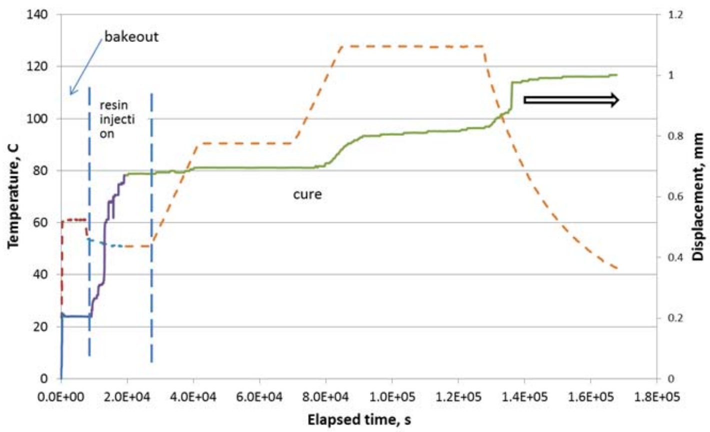

Fig. 5. Evolution of the height stack during bake out, injection and cure cycles.

2.4. Process parameters studies at GA

Evolution of the winding pack thickness was studied under different conditions at GA. First, individual conductors confirmed the effects of the glass compaction. Then, six 7x1 arrays were built and tested to study the effects of the compression on the dry stack and during impregnation and cure. After that an additional study was carried out to study number of 7781 glass layers between the pancakes in order to maintain the desired height during fabrication and in the end of the VPI process.

2.4.1. 7x1 arrays studies

Compaction of the dry array is called “preload” and the compression applied on the stack after the closure of the mold through the VPI and cure is called “active” load.

The 7x1 arrays simulated six different load scenarios:

1. Top seven layers of the CSM without preload
2. Bottom seven layers of the CSM without preload
3. Top seven layers of the CSM with preload
4. Bottom seven layers of the CSM with preload
5. Top seven layers of the CSM with preload and an active load during VPI
6. Bottom seven layers of the CSM with preload and an active load during VPI

The turn insulation was identical to the MDL arrays; test configuration was similar, except the load was applied by the pneumatic cylinders. All arrays had two layers of 7781 glass between the conductors.

The summary of the results of the 7x1 arrays study are shown in Fig. 6. The MDL 12x1 Array #1 is shown for comparison and it is consistent with the GA trials with similar scenario that provides a good cross reference. As one can see, the results indicate that a high compression of glass makes the following variation of the height small.

All data values represent the amount a seven conductor stack (7x1) has compressed from the initial height. TEST 3 data (0 Active, 1.24 bar preload) shows decreasing values from “After preload release” to “After VPI”. This trend is due to the continuous creeping spring-back of 7x1 conductor stack insulation from preload release until the end of VPI. Multiplying the 12x1 data by 7/12 represents the 12x1 VPI Test data conducted by MDL (Array #1) and scaled to compare to a 7x1 conductor stack that provides a good cross reference.

TEST 2 and TEST 5 represent the bottom 7 layers of the CSM. The “preload” was not completely removed from TEST 5. (1.24 bars) remained on the stack simulating the gravitational load of the top layers of the CSM.

The GA conclusion for the CSM pressure scenario is that the case with 0.69 bar (10 psi) preload and 0.34 bar (5 psi) active compression during VPI and cure would be optimal.

The 0.69 bar (10 psi) preload was based on the results of the following studies: Preliminary dry compression test data demonstrated approximately 75-80% of insulation compression was completed once 0.69 bar was applied to the insulation. Significantly higher loads were required to increase the amount of compression. The amount of preload considered takes into account the cost effectiveness/economics of tool design and fabrication. Applying preloads significantly higher than 0.69 bars can be disadvantageous because extremely high loads may threaten the integrity of the insulation. Additionally, more layers of glass cloth would be required in order to maintain the nominal gap thickness, yet the test data revealed that more layers of glass present in the top layers of the CSM yield greater compression/movement of the CSM during the VPI process.

The 0.34 bar (5 psi) active load was selected due to the following studies: The active load was chosen mainly to minimize the amount of compression to better control the height of the CSM during the VPI process. The 7x1 VPI Test data showed that higher active loads result in more compression/movement during the VPI process.

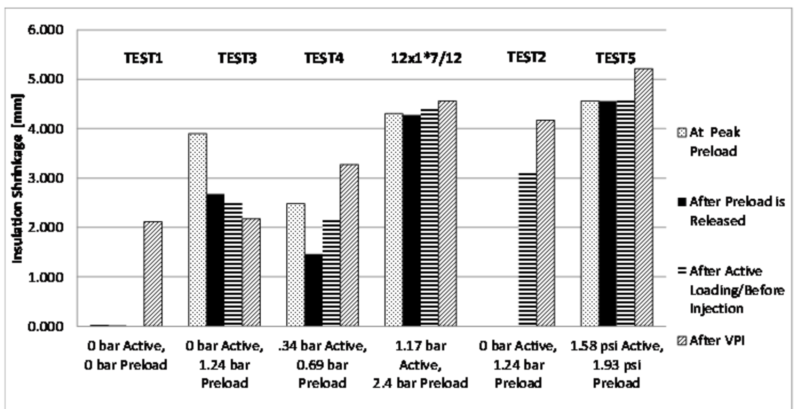

Fig. 6. Summary of the 7x1 tests at GA: shrinkage across different active loading scenarios.

2.4.2. Dry insulation compressions studies

After selection of the pressures to compact the dry insulation and to perform VPI, it was also selected to compact each hexapancake twice as the insulated conductor is assembled in the final coil configuration at the turn insulation station. Since the selected compaction pressure is significantly lower than the dead weight of the coil, it is expected that the gaps between the conductors will have different thickness at different elevation, but also, there will be some “ratcheting” taking place. In other words, several load cycles will be required in order to saturate the winding pack shrinkage. This feature was addressed by a separate study with varying number of dry glass layers between conductors. Several trials with different preload scenario, single and multiple led to the conclusion that nine layers of glass in the CSM is a good practical approach that allows controlling the overall height of the CSM with a little variation.

2.4.3. Study of the stack height with the wet glass

This study was to confirm that the dry glass compression and injection of the epoxy with the selected pressures, number of layers of glass in between the conductors and number of compactions will produce the desired overall height of the CSM. Several 3x1 arrays of a bare conductor with the different numbers of layers of glass cloth between the conductors were studied under fabrication scenario.

A summary of this study, combined with the deduced data from the turn insulation in the previous tests, is shown in Fig. 7; it gives the change in conductor-to-conductor gap as a function of the number of glass layers (or shims).

Most of the compression/movement seen during VPI is due to the movement of the top layers of the CSM. This is because the lower layer thickness has already reached near steady state due to the multiple preload cycles and gravitational loading of the upper layers of the CSM.

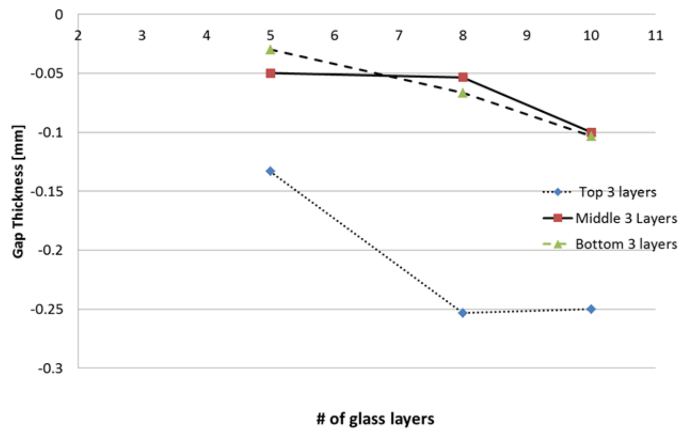

Fig. 7. Change in conductor-to-conductor gap thickness during VPI. (This includes the application of active load before injection).

The height of the coil layers will vary during the fabrication process, up until the last pancake and compaction. It will be slightly oversized, since every cycle of the compaction will somewhat reduce the height of the insulation in the pancakes already laid on the assembly table. With the selected fabrication scenario, the top layers remain a little fluffy and contribute disproportionally to the height shrinkage under the load during the VPI procedure. This observation leaves some adjustment capability of the height stack between increasing the compression during the VPI or reducing number of glass layers in the upper turns and reducing the pressure during VPI.

The expectations of the insulation shrinkage, based on the analysis of the available data are shown in Fig. 7. It shows that the top six layers (40-through 35) experience more movement during VPI. The lower layers (starting from the layer 1) experienced more load due to gravity and compression cycling of the CSM during buildup (prior to VPI).

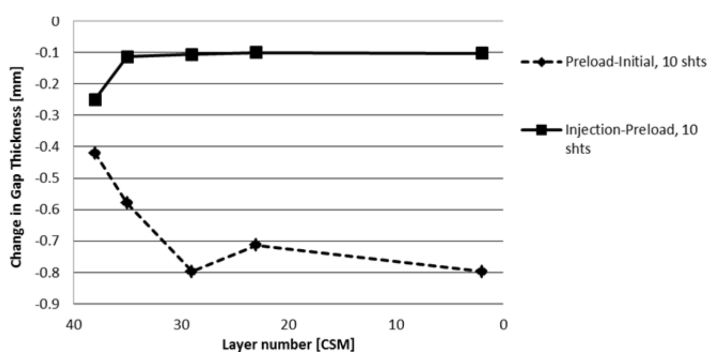

Fig.8. Change in gap thickness across CSM layers with 10 layers of glass between the conductors.

In order to simplify the Turn Insulation station process while both minimizing VPI shrinkage and reaching the nominal spacing between the conductors, we recommend using equal number of layers (nine) between the pancakes in the CSM.

The final fabrication procedure will be verified during assembly of the full scale mockup prior to fabrication of the production CSM that will be used in the ITER machine. There are some unknowns that could not be addressed on the straight conductor studies, like the wound coil springiness, only a real coil configuration can reveal all the issues.

3. Conclusions

Intensive study of the shrinkage of the heavy winding packs revealed that the insulation develops shrinkage and creep that makes management of the coil height a challenging task. This is a very relevant problem for the ITER CSM. This phenomenon requires active management of the coil height by careful selection of the dry insulation thickness, fabrication steps of compaction the glass during assembly, before impregnation and in the mold during VPI and cure. The main conclusion is that the uncertainty of the coil height can be overcome by compaction of the glass while dry and during impregnation. As a result of this effort we developed a credible height management scenario, which will be verified on a full scale prototype in the nearest future.

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